91602
new 82-10

ontario hydro
research division

To: Mr. O. Bernaus
Manager
Civil Maintenance
Hydraulic Generation Group

INSTRUMENTATION OF REINFORCED EARTH WALL

C.B.H. Cragg

The use of a reinforced earth wall for shoreline rehabilitation at Cardinal, Ontario was the first time this type of construction had been placed underwater. Differential movements of 10 mm to 30 mm were anticipated between the concrete wall panels and the granular backfill. Actual measured movements agreed well with these predictions. Instrumentation, monitoring methods and measured results are presented in detail in this report.

1.0 INTRODUCTION

Reinforced earth wall construction was pioneered by Vidal in 1964/1/ and has since become an accepted practice in Europe and, more recently, in Canada. However, the use of reinforced earth wall construction for shoreline repairs at Cardinal, Ontario, where the ice boom for the R.H. Saunders GS dam is deployed, was unique because it was constructed underwater. As shown in Figures 1 and 2, the wall is 48 m (approximately 12 panels) long and 4.3 m (2 panels) high. Normal water level in the St. Lawrence River is about half way up the upper wall panel. Four layers of steel reinforcing strips, two per panel, hold the wall in place. Crushed stone with a maximum size of 40 mm was used to backfill behind the wall (grading curve Figure 3) and around the reinforcing strips. As the backfill was expected to settle 10 mm to 30 mm relative to the wall panels/2/, the connection of the reinforcing strips to the wall panels was designed to permit movement. The wall was instrumented to monitor its performance during and after construction. Details of the instrumentation and monitoring results are presented in this report.

2.0 INSTRUMENTATION

2.1 Purpose of Instrumentation

Instrumentation was installed to monitor movement of the backfill soil relative to the concrete wall panels and geotechnical aspects of the project related to performance of the reinforced earth wall. Specific measurements were taken to:

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

(a) monitor absolute and relative movement of the upper and lower wall panels (note: a layer of compressible cork is sandwiched between the panels - Figure 2)

(b) monitor density of the backfill

(c) monitor movement of the steel reinforcing strips relative to the concrete wall panels, and

(d) monitor the settlement of the backfill soil at locations remote from the concrete wall.

2.2 Monitoring Methods

Two sections of the reinforced earth wall were instrumented at the locations shown in Figure 1. At each section, a settlement rod, two horizontal profiler tubes, two hydraulic strain gauges and a downhole density testing tube were placed at the positions shown in Figure 2. Details of each instrument are given in the following sections.

2.2.1 Settlement Rods

The settlement rods rested on an angle bracket attached to the lower wall panel and were held in place by a vertical sleeve attached to the upper wall panel at each section (see Figure 4). Elevation surveys on the rods and on the top of the upper wall panel were used to determine compression of the cork separating the panels. Total settlement of the panels was not obtained. Readings were referenced to a temporary benchmark remote from the construction activity on the site.

2.2.2 Horizontal Profilers

Horizontal profiler tubes, 32 mm in diameter and up to 15 m long, were placed in the backfill at the same elevation as the upper reinforcing strips for the lower panel and the lower reinforcing strips for the upper panel. As shown in Figure 5, the profiler tubes are sleeved through the concrete wall panels between the reinforcing strips and both ends of the tube are raised above finished grade elevation. After filling the profiler tubes with water, a pressure transducer was used to establish elevations at 0.3 m intervals along the tube by measuring relative water pressures. The point of attachment of the tube to the wall panels was used as the reference point for determining elevations. Readings of these gauges provide information on settlement of the backfill at points remote from the wall panels and, by inference, give an indication of the installed position of the adjacent steel reinforcing strips.

2.2.3 Hydraulic Strain Gauges

Hydraulic strain gauges consist of a water filled cylinder and a plunger similar in construction to a hypodermic syringe. The cylinder was attached to the concrete wall panel and the plunger was attached, via a connecting rod, to the reinforcing steel strips (Figure 6). A smaller diameter tube attached to the cylinder extends to a sight gauge remote from the monitoring point. Movement of the strain gauge piston results in a change in water level in the smaller tube at the sight gauges. Small movements of the piston are magnified by using a sight gauge tube smaller than the strain gauge cylinder. These gauges, with 12 times magnification, have been used with great success to

monitor strains in geotextiles reinforcing embankments over soft soil/3/. The magnification factor was increased to 18.5 times for the hydraulic strain gauges used on this project. A dummy sight tube was installed to correct readings for temperature changes.

The hydraulic strain gauges were installed at the same reinforcing strip elevations as the horizontal profilers.

Readings from the hydraulic strain gauges give a direct measurement of the relative movement between the backfill and the concrete wall panels.

2.2.4 Density Tests

Plastic access tubes, approximately 50 mm in diameter, were positioned 300 mm behind the wall to allow measurements of the backfill density using the downhole nuclear density gauge. A typical access tube is shown on Figure 5a. Gauge readings are calibrated to the specific backfill using a laboratory procedure described elsewhere/4/.

3.0 INSTALLATION AND MONITORING

All gauges, except density access tubes, were attached to the wall panels prior to placement offshore. Lower panel profile tubes were attached to the same supporting cages used to keep the reinforcing strips in place while backfill was being placed. Initial readings on these gauges were taken after backfill had been placed to about the top of the lower panels. Upper panel profile tubes were placed on top of the completed backfill in the dry and then buried. Initial readings for these profilers were taken as soon as they were placed and before burial. Initial readings for settlement rods and hydraulic strain gauges were obtained as soon as these gauges were in place. The initial readings were obtained about August 23, 1988, during construction. A second set of readings were taken immediately after completion of construction on September 8, 1988. A third and final set of readings was obtained October 7, 1988.

4.0 MONITORING RESULTS

Relative movement of the earth fill versus the wall panels is shown by the hydraulic strain gauge readings in Table I. Movements ranging from 7.7 mm to 26.1 mm (0.30 to 1.03 inch) were recorded. The gauge on the foundation panel at Section 2 yielded no data due to damage during fill placement. An estimate of movement at this location is shown in Table I, based on calculations described below.

Compression of the cork between the upper and lower concrete panels ranged from 5.0 to 19.0 mm (0.20 to 0.75 inch) as shown in Table I. The larger compression is associated with Section 2 where two layers of cork had been placed.

Figures 7 and 8 show the positions of the profilers at Sections 1 and 2 at the end of construction. Figures 9, 11, 13 and 15 show the elevations of each profiler at each of the monitoring dates (August 23, September 8 and October 7). Figures 10, 12, 14 and 16 show the settlement at each profiler relative to the initial readings. No September 8 reading was obtained at the Section 2 lower profiler because the tube had been pinched by a boulder in the fill near the land side access to the profiler (see Figure 5b). All profiler readings

were interpreted relative to the reading obtained immediately next to the concrete wall panel connection. As the "zero" profiler readings were obtained at least 75 mm (3 inches) behind the wall panel, these readings (and all other readings related to them) have been increased by the amount of the relevant hydraulic strain gauge readings. In the 3 m (10 feet length of profiler) immediately behind the wall, settlements of 25 to 75 mm (1 to 3 inches) were recorded at the Section 1 lower profiler and the Section 2 upper profiler, while settlements increasing up to 150 mm (6 inches) were recorded at the other two profilers. Little additional settlement was observed at Section 1 after September 7, but up to 40 mm (1.5 inch) of extra settlement was observed at Section 2. Considerable variation in elevation occurred along the length of each profiler in the 7 m (24 foot) wide zone immediately behind the wall where the reinforced earth strips were installed.

No density readings were obtained due to malfunction of the nuclear depth density equipment at the time of construction and the inability to obtain repairs for some months after construction.

5.0 DISCUSSION

Difficulties encountered in this monitoring program have resulted in less data being collected and less opportunity to verify data accuracy than was originally desired. Nevertheless, reading checks and estimates of values for defunct reading sites are made with the available information. A number of simplifying assumptions are necessary to support these checks and estimates. These are:

(1) Settlement of the reinforced earth wall footing is small, elastic and immediate.

(2) Settlement of the river bottom under the earth fill is also small, elastic and immediate.

(3) Penetration of the granular fill into the river bottom occurs immediately and does not affect the differential movements seen by the lower (foundation panel) hydraulic strain gauges.

(4) The reinforcing strips (attached to the hydraulic strain gauges) and the profiler tubes move with the fill relative to the wall panels.

The instrument readings may then be interpreted and related in the following manner. Deformations of the lower hydraulic strain gauges and lower profilers are indicative of the densification of fill between the lower reinforcing strips and the river bottom caused by placement of fill and construction activity (compaction) above this level. Settlement rod readings indicate the movement of the upper wall panel relative to the lower wall panel and, by inference, the compression of the cork layer between the panels. The movement of the upper hydraulic strain gauges and upper profilers indicate compression of the fill between this level and river bottom minus any movement of the upper panel relative to the lower panel (ie compression of the cork). Since the distance from river bottom to the level of the lower panel instrumentation is approximately equal to the distance between the upper and lower instrumentation levels, movement of the upper gauges should be double that of the lower gauges minus compression of the cork. Or, conversely, movement of the lower gauges should be one half the sum of the top gauge and cork deformation values. Provided all the fill is placed loose and left

uncompacted until the upper reinforcing strips (and gauges) are installed, the above relations should hold. However, river water level was at or just below the level of the upper instrumentation (Figure 5a) allowing equipment to operate on and densify the fill prior to placement of the upper reinforcing and gauges. As a lower bound, the upper gauges are estimated to undergo the same movement as the lower gauges; less compression of the cork since most of the construction equipment activity on and compaction of the fill took place after placement of the upper gauges. Table I shows that the "top estimate" values obtained by these relationships bracket the actual top strain gauge reading for Section 1 on September 8, but underestimate the actual value for October 7. The "foundation estimate" values in Table I were obtained from the same relationships. As the internal check of the Section 1 readings only produced "ballpark" agreement with actual readings, the foundation estimates for Section 2 can only be regarded as "ballpark" indicators of actual movements. In spite of these reservations and limitations, the differential movements of the fill relative to the concrete wall and their estimates almost all fall in the predicted range of 10 mm to 30 mm.

Figures 7 and 8 show that, on a macro scale, the profilers (and by inference the reinforcing strips) are horizontal and straight as assumed in analysis. An enlarged view of the profilers (Figures 9, 11, 13, 15) shows an undulating shape indicating that the pullout resistance of the reinforcing is enhanced by interlock with the fill in addition to friction. The pattern of the undulations suggests rutting caused by the passage of vehicles over the strips. The patterns of settlements (Figures 10, 12, 14 and 16) are also suggestive of rutting caused by two wheels or tracks passing perpendicular to the strips. Most of the strips exhibit two zones of larger settlements separated by a zone of minor settlement. The "rut" areas ranged from about 75 mm to about 150 mm. Virtually all settlement occurred during construction (prior to Sept 8) and, with the exception of upper profiler 2, no significant additional settlement occurred in the period from September 8 to October 7 after construction. Higher elevations for the lower profilers may also correspond to locations of supporting cages. At distances beyond the second support from the wall panels, lower profiler 2 may not be representative of the movement of the reinforcing strips (Figure 16) because attachment to the shore did not allow free movement downwards. From Figures 17 to 20, it may be seen that the magnitude and pattern of the settlements of the fill near the wall are similar at all sections. The similarity is particularly strong for upper section 1, upper section 2 and lower section 1 in the 2 m nearest the wall panels. Lower panel 2 was constructed much prior to work at the other three panels so that differences in construction method may account for differences in performance. There is some similarity in settlement patterns for lower sections 1 and 2 away from the wall panels. The cages used to support the reinforcing strips during lower panel installation are believed responsible for these similarities. The shape of the profilers should be examined in more detail to ensure the construction process has not locally overstressed the reinforcing strips in bending, weakening the structure. Apart from this concern, the manufacturers are to be commended for their realistic prediction of differential movement at the fill/wall interface and the inclusion of flexible reinforcing connections at the wall with adequate play to accommodate the monitored movements.

6.0 SUMMARY

The relative movements of the reinforced earth wall panels and differential settlement of the earth fill was successfully monitored at Cardinal, Ontario. Absolute wall movements and fill density measurements were not obtained. The differential settlements agree well with the manufacturer's prediction of movements in the 10 mm to 30 mm range. Adequate flexibility was built in the reinforcing strip to wall panel connection to accommodate these movements while maintaining anchorage for the panels. Profiler readings indicate the reinforcing strips attained an undulating shape after construction which should enhance their pullout resistance by adding an interlocking component to the basic frictional based capacity. The undulating shape is believed to have been developed by the rutting action of vehicles during construction. A review of the deformed shape of the reinforcing strips is suggested to check that the strips have not been overstressed in bending due to the rutting process.* As the fill movements observed were generally immediate and confined to the construction period, no long term movements are anticipated. If the reinforcing has not experienced overstress then the wall is expected to perform well in the long term.

ACKNOWLEDGMENT

The resourcefulness of Mr. M. Grills in fabricating and monitoring the instrumentation and in particular, effecting installation on very short notice is gratefully acknowledged. The assistance of the manufacturer, the cooperation of the construction forces and the sponsorship of Civil Maintenance is also greatly appreciated.

Approved by:

T.W. Klym
Manager
Civil Research Department

Prepared by:

C.B.H. Cragg
Senior Engineer
Soil Sciences Section

Reviewed by:

T.J. Carmichael
Supervising Engineer
Soil Sciences Section

CBHC:LM

*A review by the manufacturer confirmed that the stresses within the reinforcing strips were within allowable limits. Stresses due to bending were calculated to be 60 MPa. Tensile stress was calculated to be 200 MPa. Allowable tension in the strips was 350 MPa.

REFERENCES

1. Vidal, H. "A Brief History of Terre Armee (Reinforced Earth)". Revue Generale des Routes et des aerodromes, No 635, November, 1986.

2. personal communication with D. Weinreb, Reinforced Earth Co Canada.

3. Dunnicliff, J. (1988) Geotechnical Instrumentation for Monitoring Field Performance, 577 p, J.Wiley & Sons (hydraulic strain gauge p 314).

4. "The Simulated B-Parameter Method of Nuclear Density Gauge Calibration and Field Survey Data Analysis". Report by L. Robert Kimball Associates, 21 pp, 1988.

TABLE I

Cardinal Reinforced Earth Wall

Differential Settlement of Earth Fill Relative to Concrete Wall Panels and Compression of Cork Interpreted from Hydraulic Strain Gauge and Settlement Rod Readings

Location		Fill Settlement/Cork Compression			
Wall Section	Panel Level	Sept 8 (mm)	Oct 7 (mm)	Sept 8 (in)	Oct 7 (in)
1	Top	7.7	11.1	0.30	0.44
	Cork	5.0	16.0	0.20	0.63
	Foundation	10.9	12.1	0.43	0.48
	Top Estimate	5.9-16.8	0.0-8.2	0.23-0.66	0.0-0.32
2	Top	11.0	26.1	0.43	1.03
	Cork	16.0	19.0	0.63	0.75
	Foundation	N/A	N/A	N/A	N/A
	Foundation Estimate	13.5-27.0	22.6-45.1	0.53-1.06	0.89-1.78

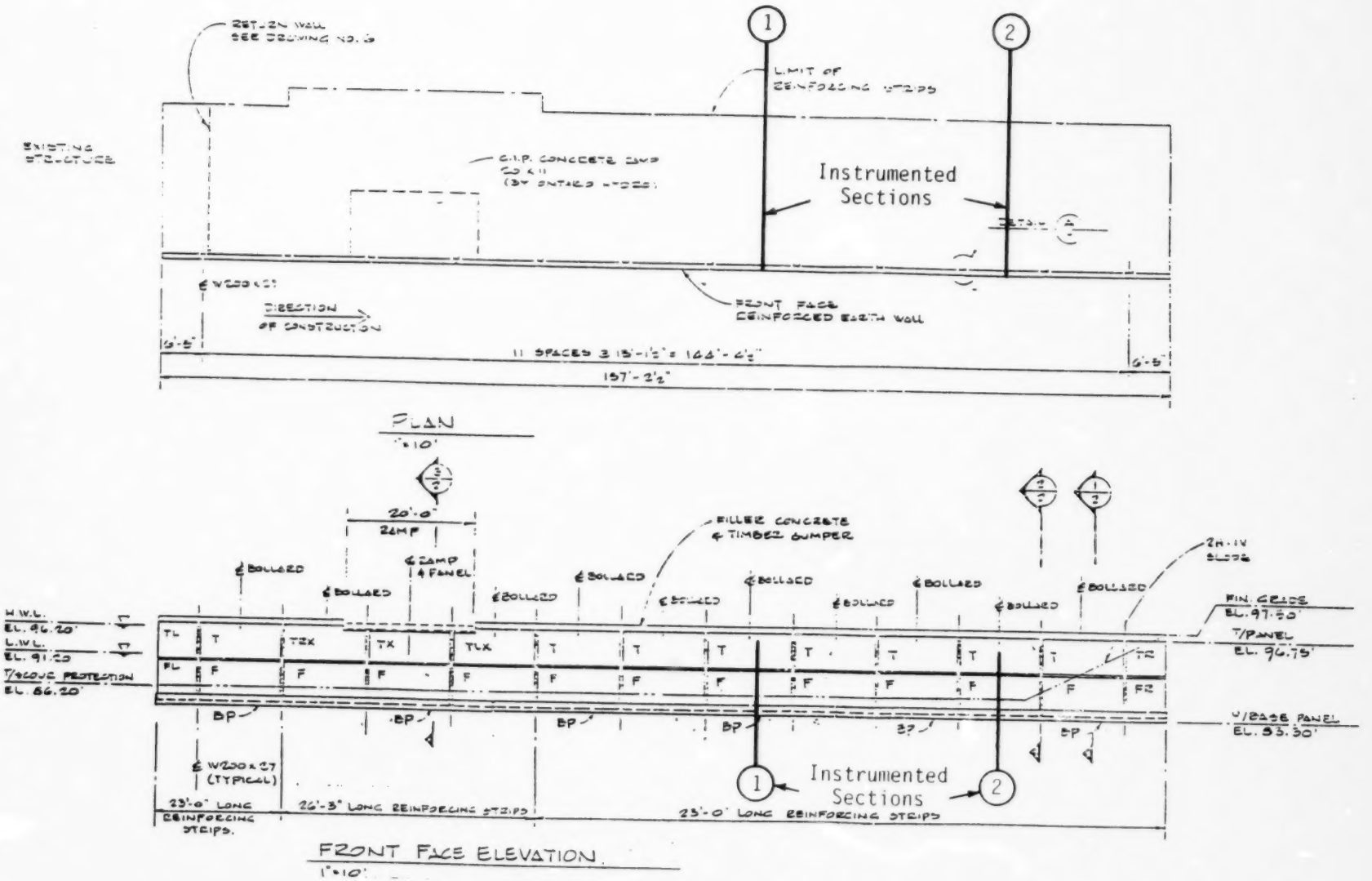


FIGURE 1 PLAN & ELEVATION OF REINFORCED EARTH WALL AT CARDINAL, ONTARIO SHOWING LOCATIONS OF INSTRUMENTATION

89-215
181797-RD

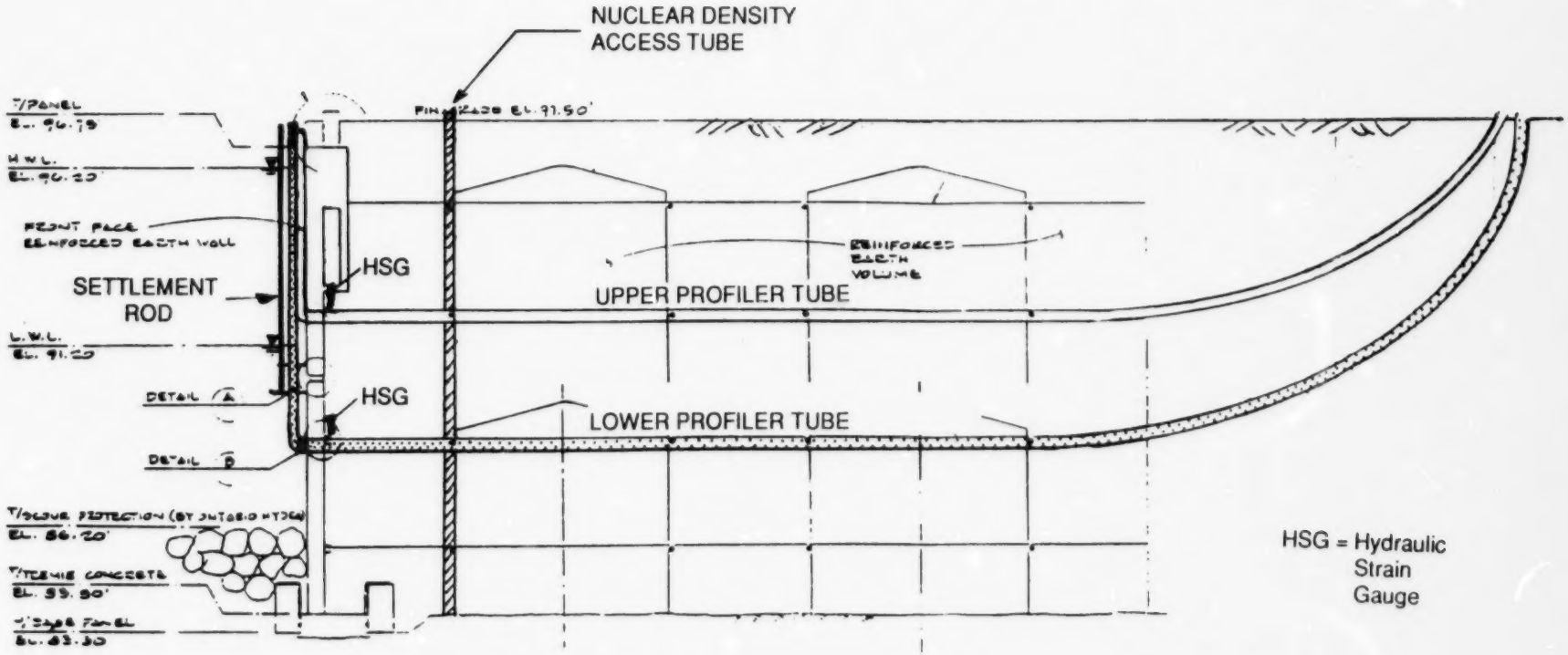


FIGURE 2 SECTION OF REINFORCED EARTH WALL AT CARDINAL, ONTARIO SHOWING INSTRUMENTATION

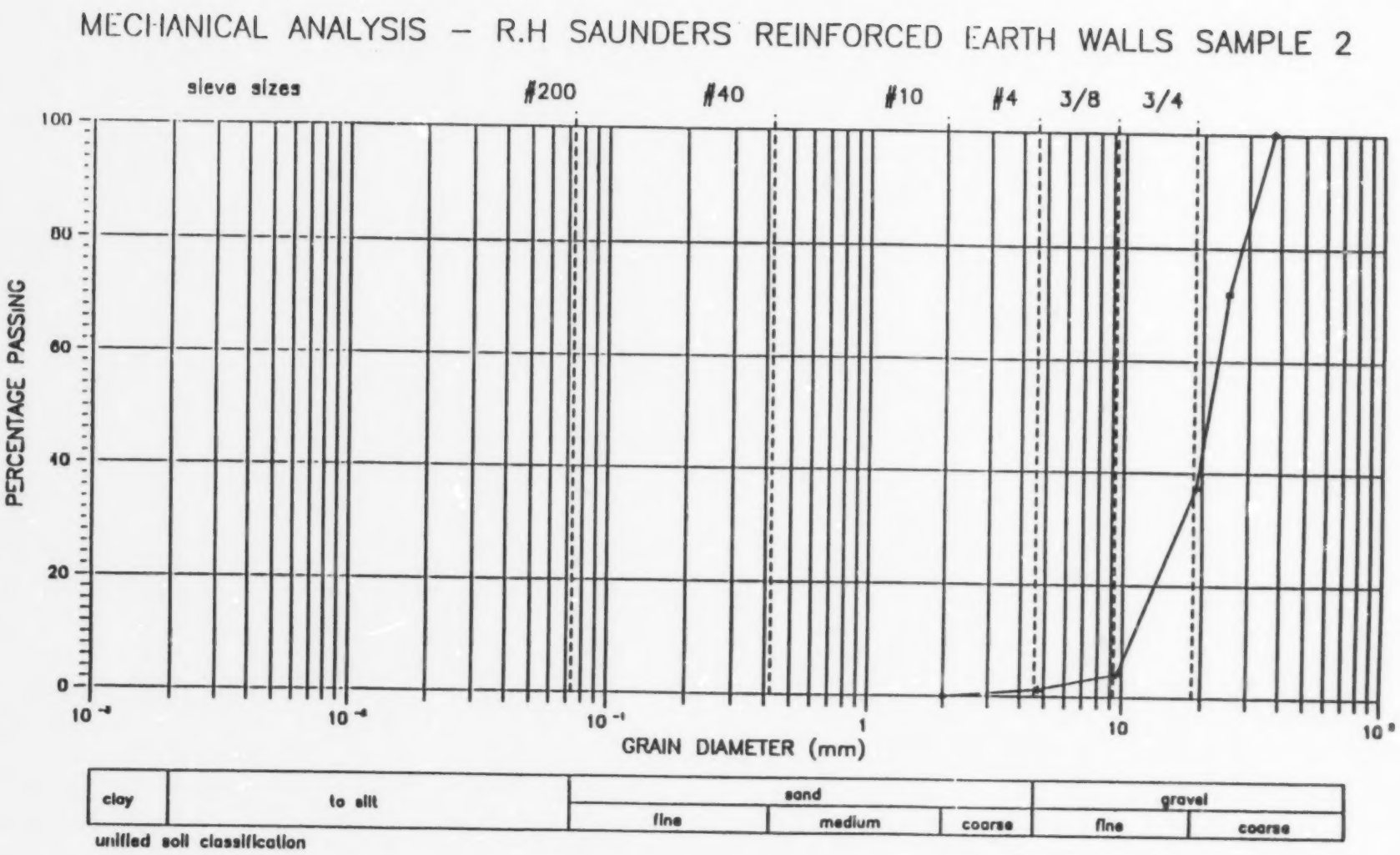


FIGURE 3 GRAIN SIZE DISTRIBUTION FOR FILL USED TO CONSTRUCT THE REINFORCED EARTH WALL AT CARDINAL, ONTARIO

ONTARIO HYDRO
RESEARCH DIVISION

89-215
181762-RD

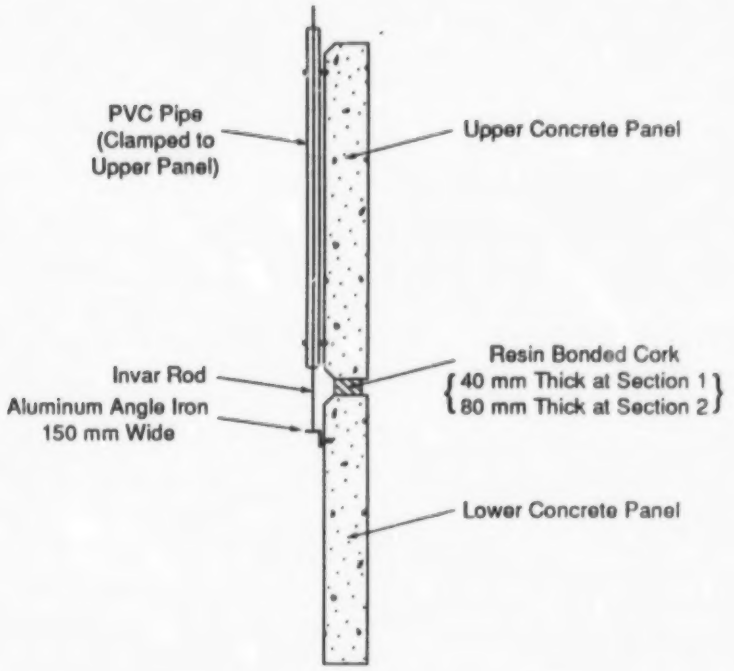


FIGURE 4(a) DETAILS OF SETTLEMENT RODS USED AT REINFORCED EARTH WALL AT CARDINAL, ONTARIO

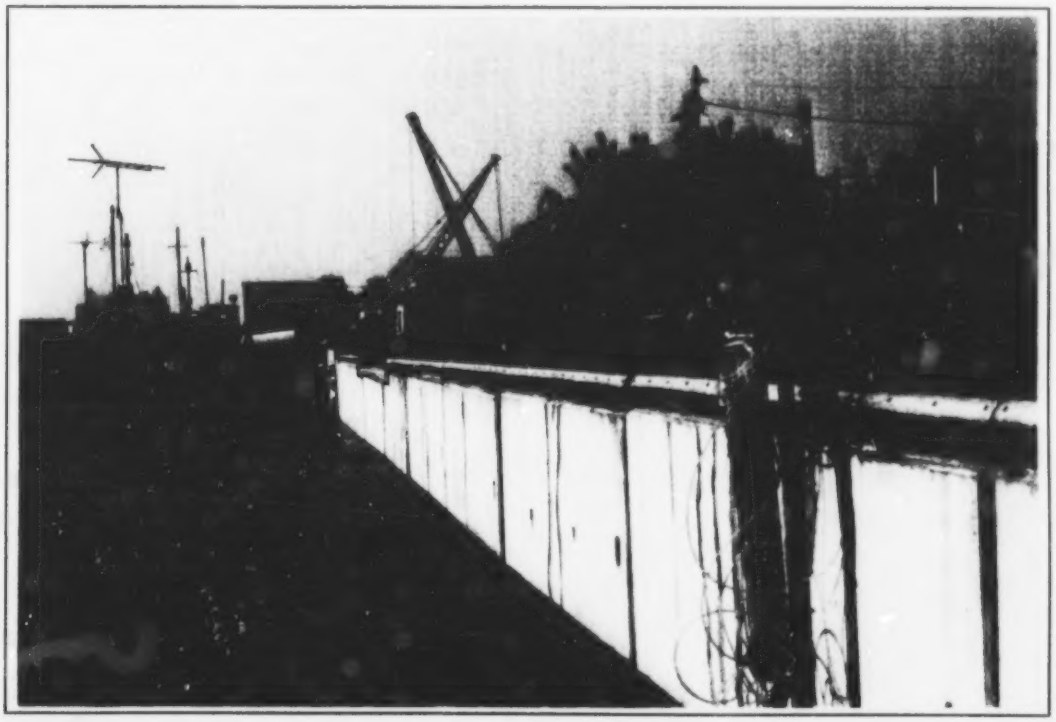


FIGURE 4(b) VIEW OF COMPLETED REINFORCED EARTH WALL FROM RIVER SIDE SHOWING (left to right, foreground) HYDRAULIC STRAIN GAUGE READOUT BOARD, PROFILER TUBE AND SETTLEMENT ROD SLEEVE

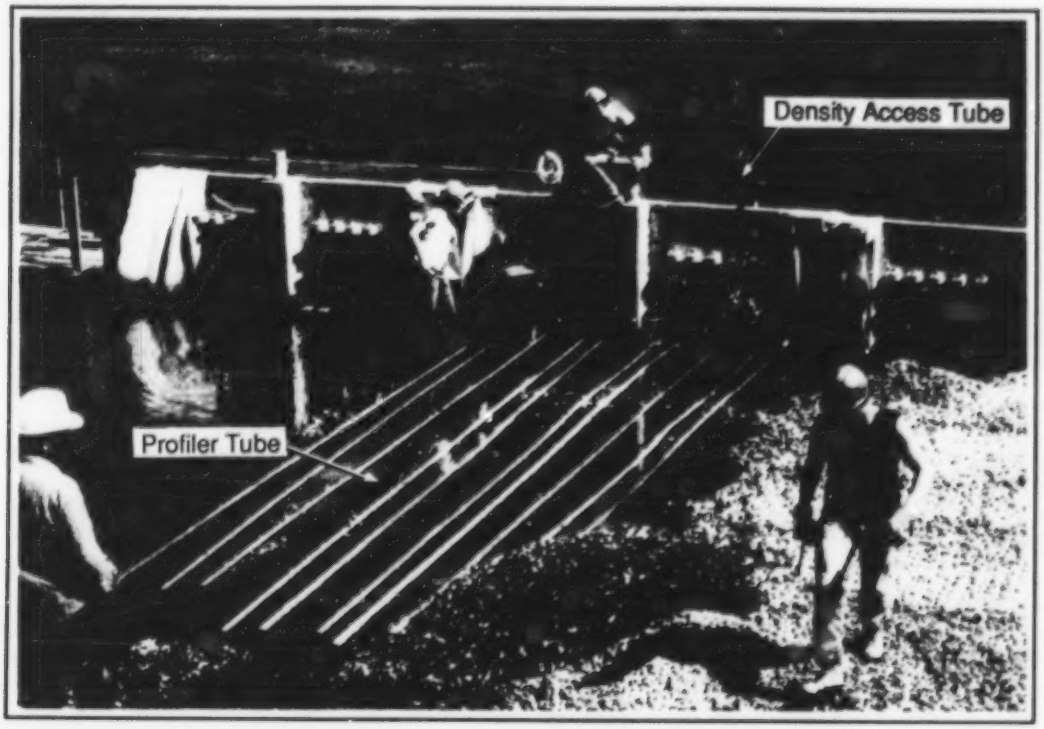


FIGURE 5(a) PROFILER TUBE AND REINFORCING STRIPS ON UPPER WALL PANEL, DURING CONSTRUCTION

FIGURE 5(a) LAND SIDE EXIT OF PROFILER TUBES AT REINFORCED EARTH WALL, CARDINAL - SECTION 1 PROFILER (Background, Left), SECTION 2 PROFILER (Background, Left), SECTION 2 PROFILER (Foregound, Center) NOTE BOULDERS

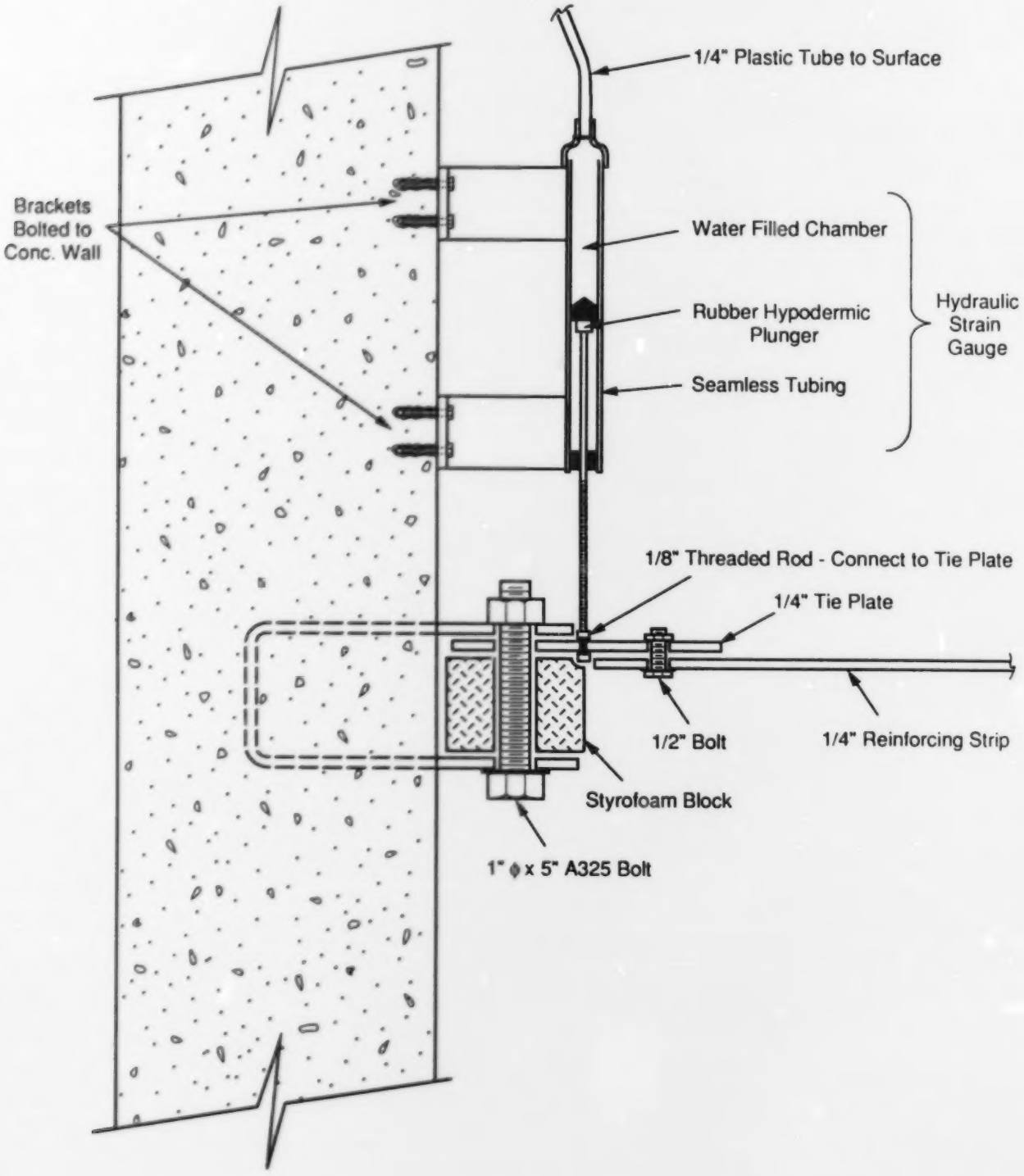


FIGURE 6(a) DETAILS OF HYDRAULIC STRAIN GAUGES AT REINFORCED EARTH WALL, CARDINAL, ONTARIO

FIGURE 6(b) VIEW OF HYDRAULIC STRAIN GAUGE CONNECTION TO REINFORCING STRIP

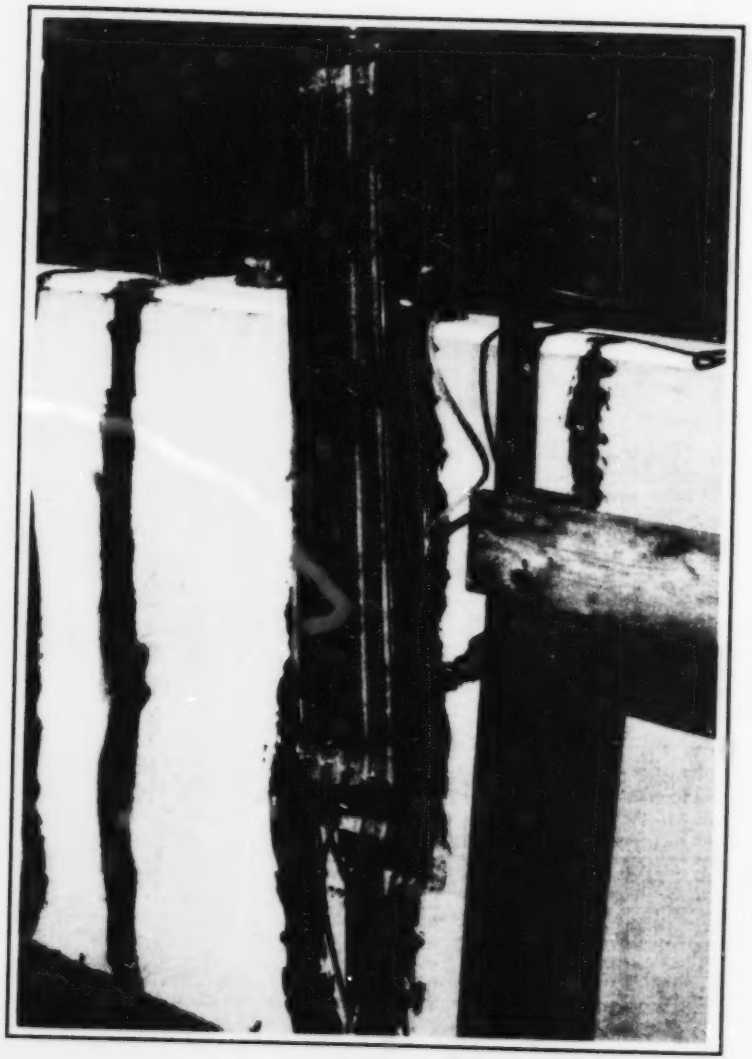


FIGURE 6(c) READOUT BOARD FOR HYDRAULIC STRAIN GAUGES

FIGURE 7: CARDINAL REINFORCED EARTH WALL

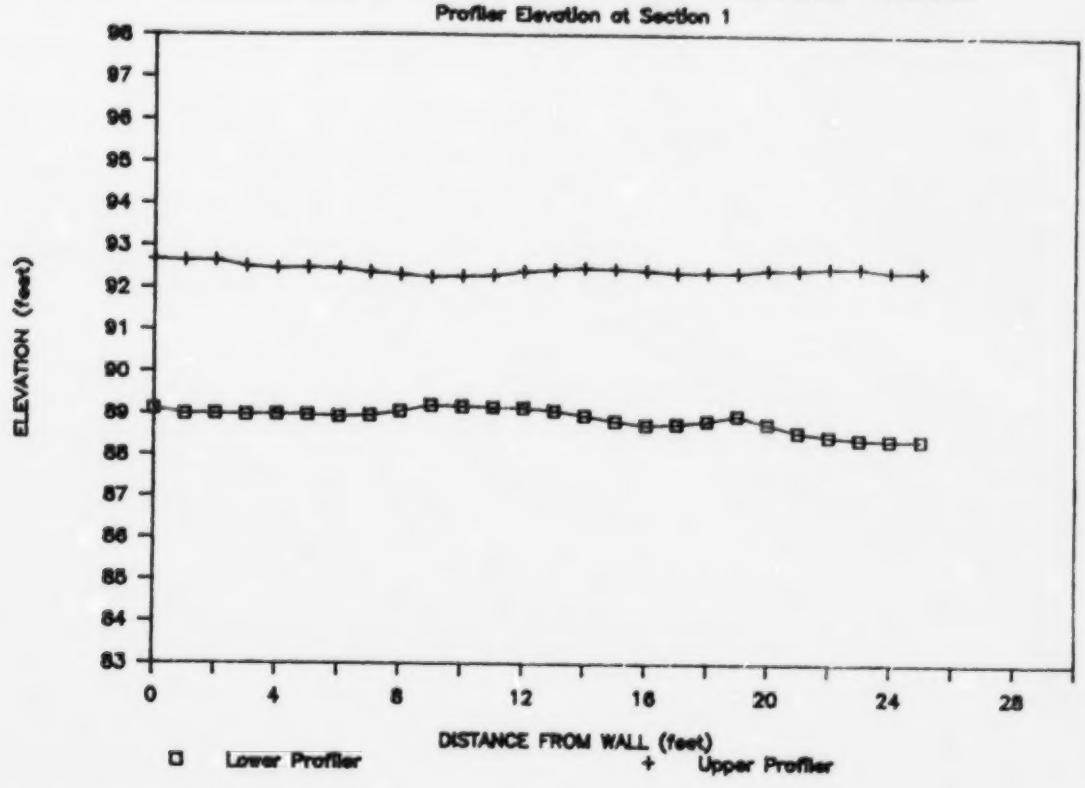


FIGURE 8: CARDINAL REINFORCED EARTH WALL

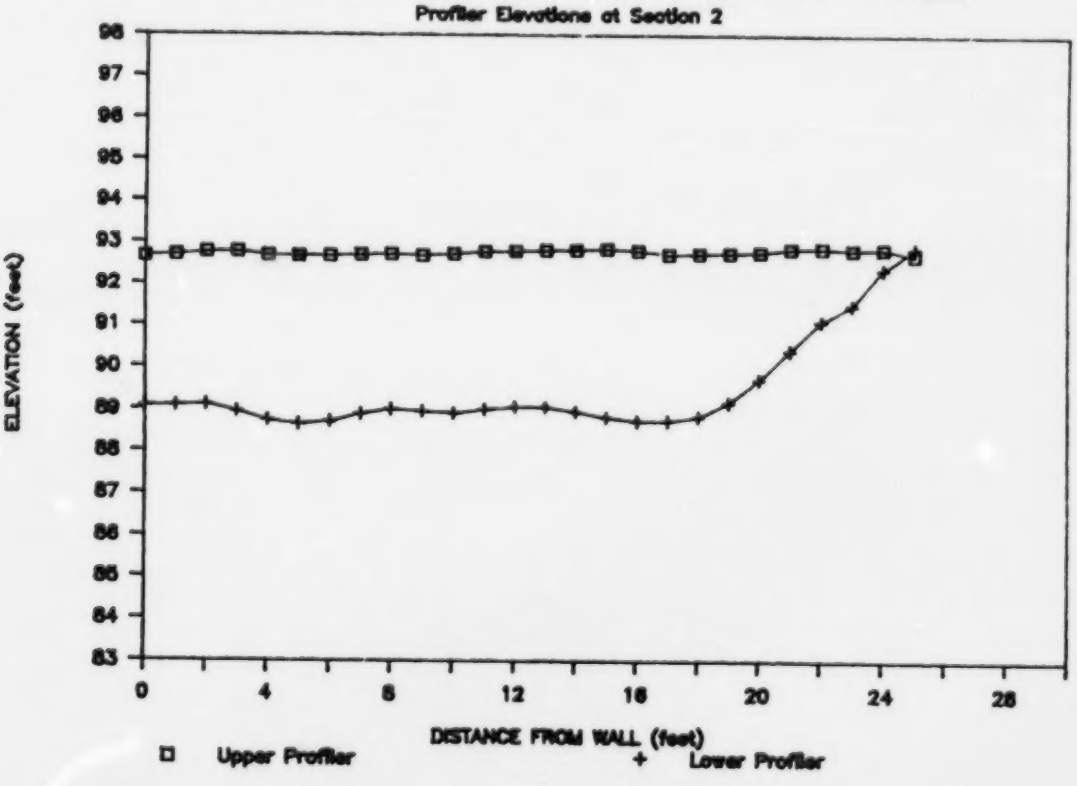


FIGURE 9: CARDINAL REINFORCED EARTH WALL

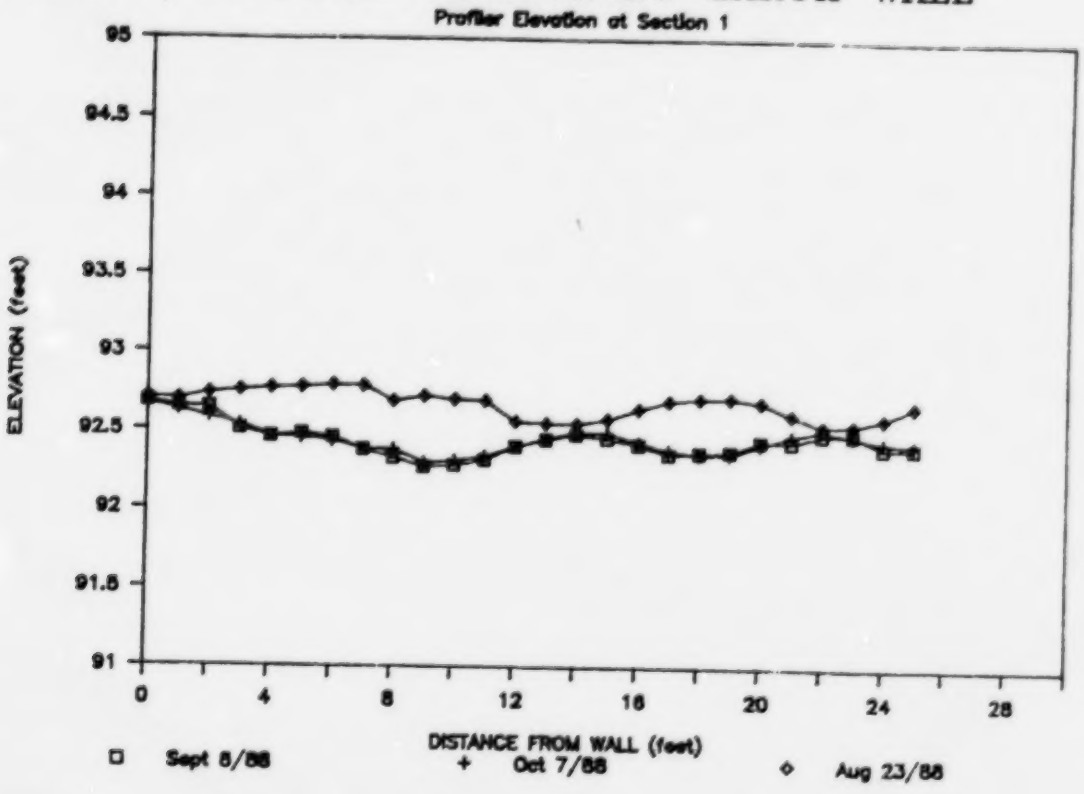


FIGURE 10: CARDINAL REINFORCED EARTH WALL

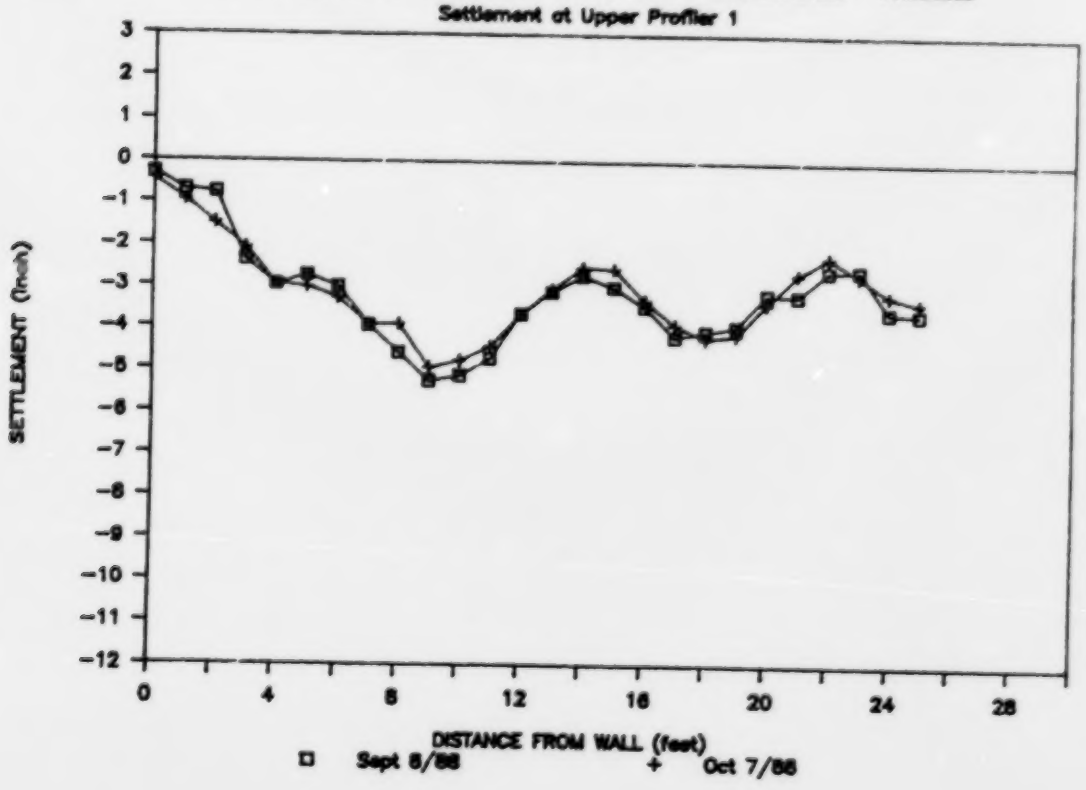


FIGURE 11: CARDINAL REINFORCED EARTH WALL

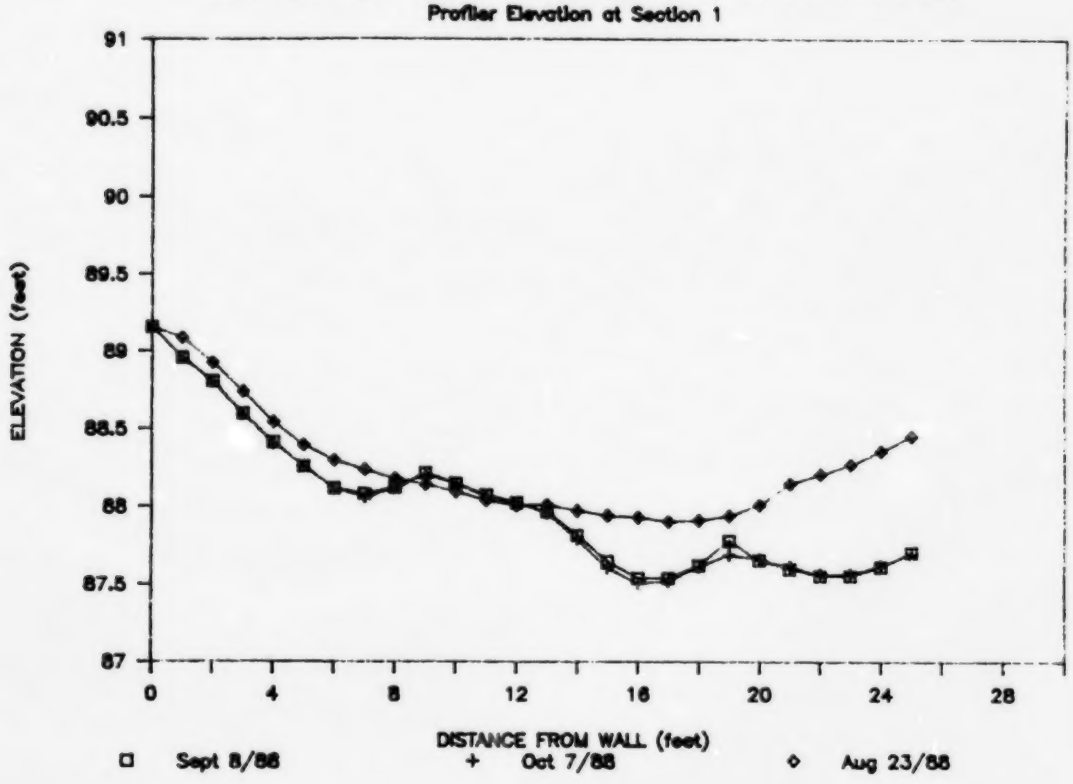


FIGURE 12: CARDINAL REINFORCED EARTH WALL

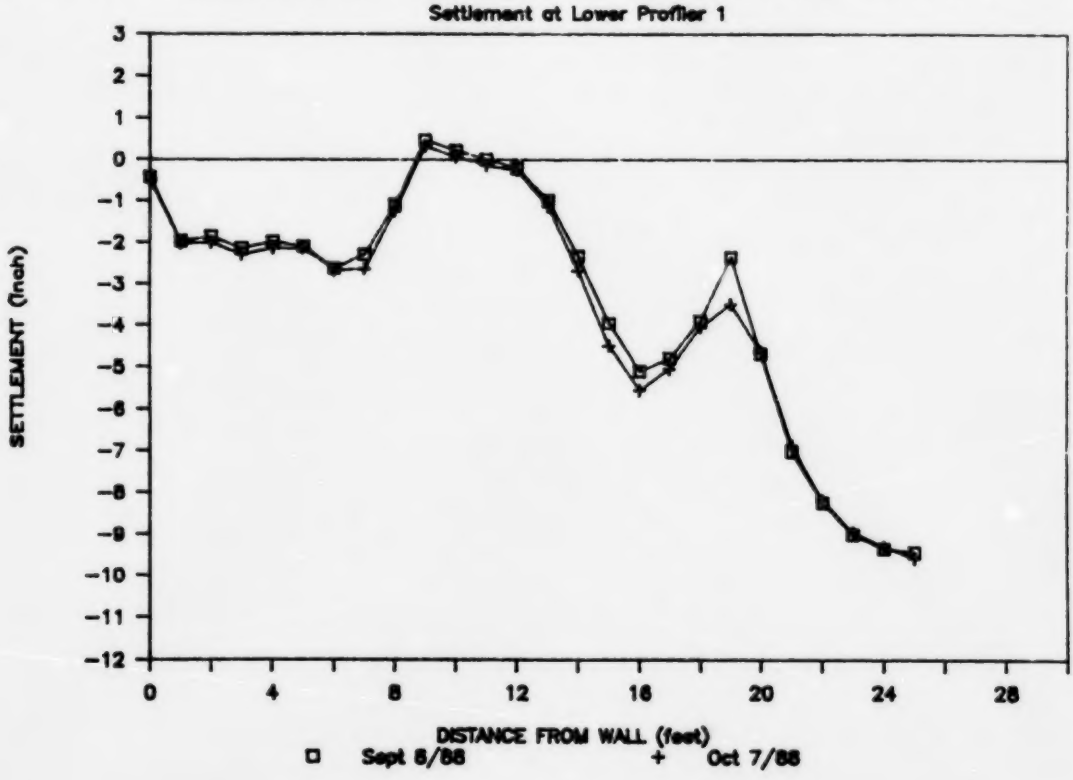


FIGURE 13: CARDINAL REINFORCED EARTH WALL

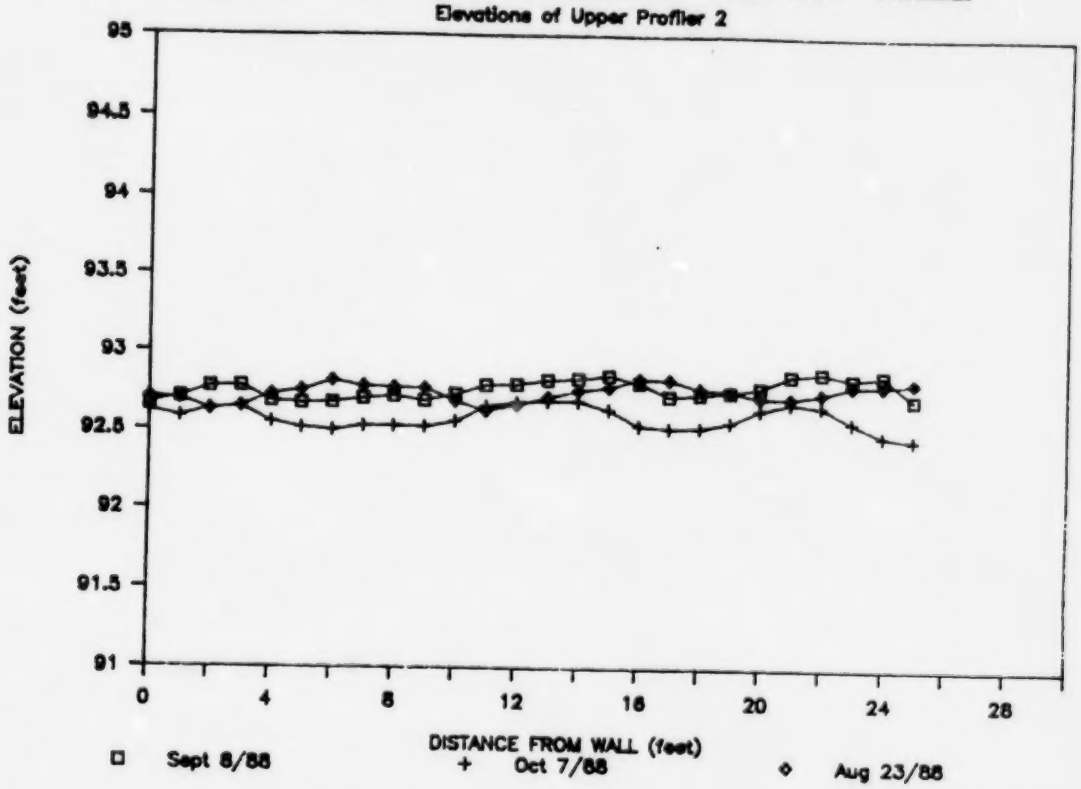
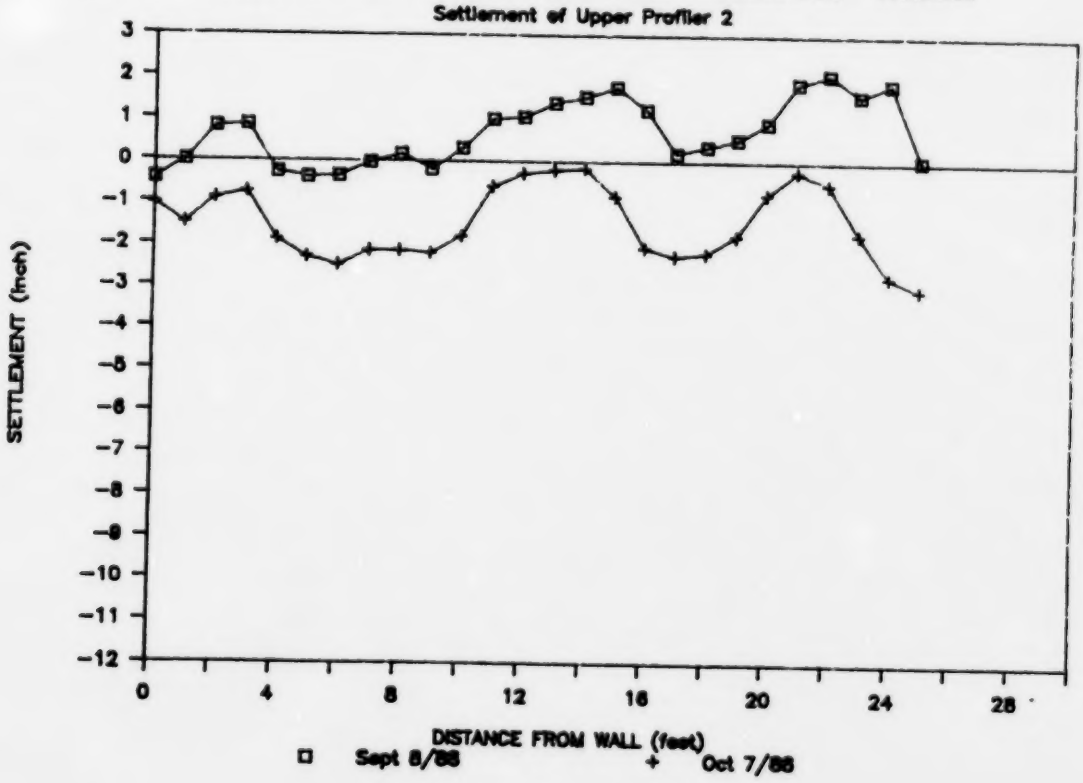


FIGURE 14: CARDINAL REINFORCED EARTH WALL



89-215
181758-RD

FIGURE 15: CARDINAL REINFORCED EARTH WALL

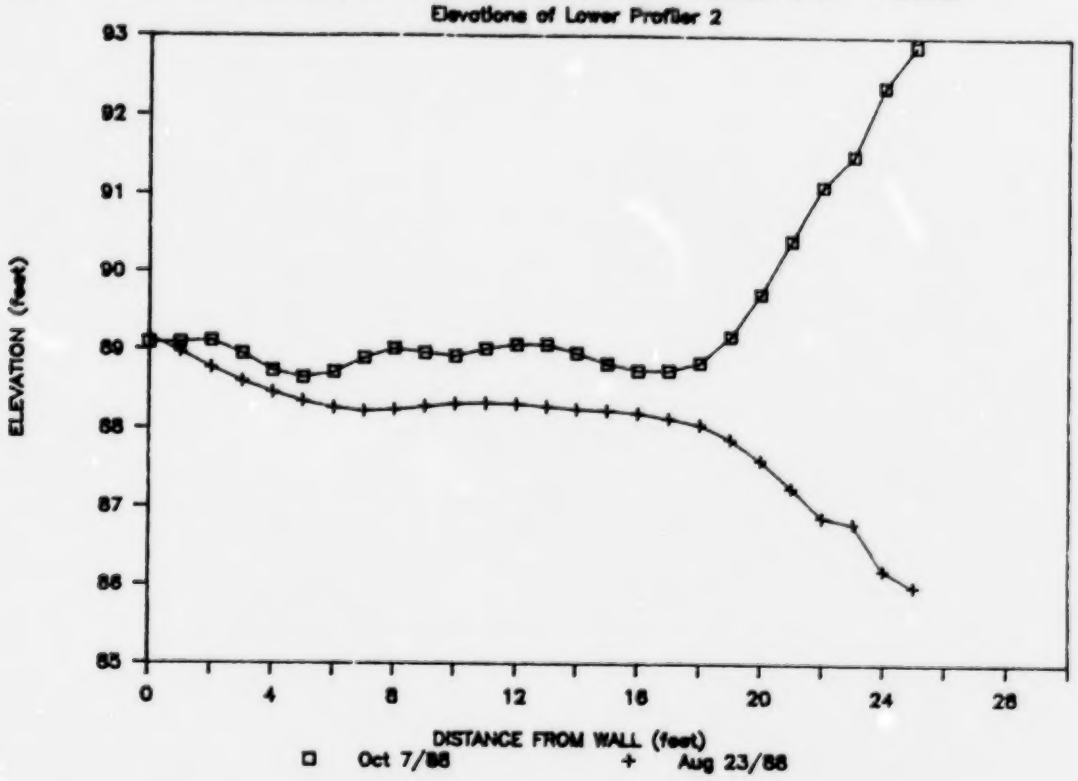
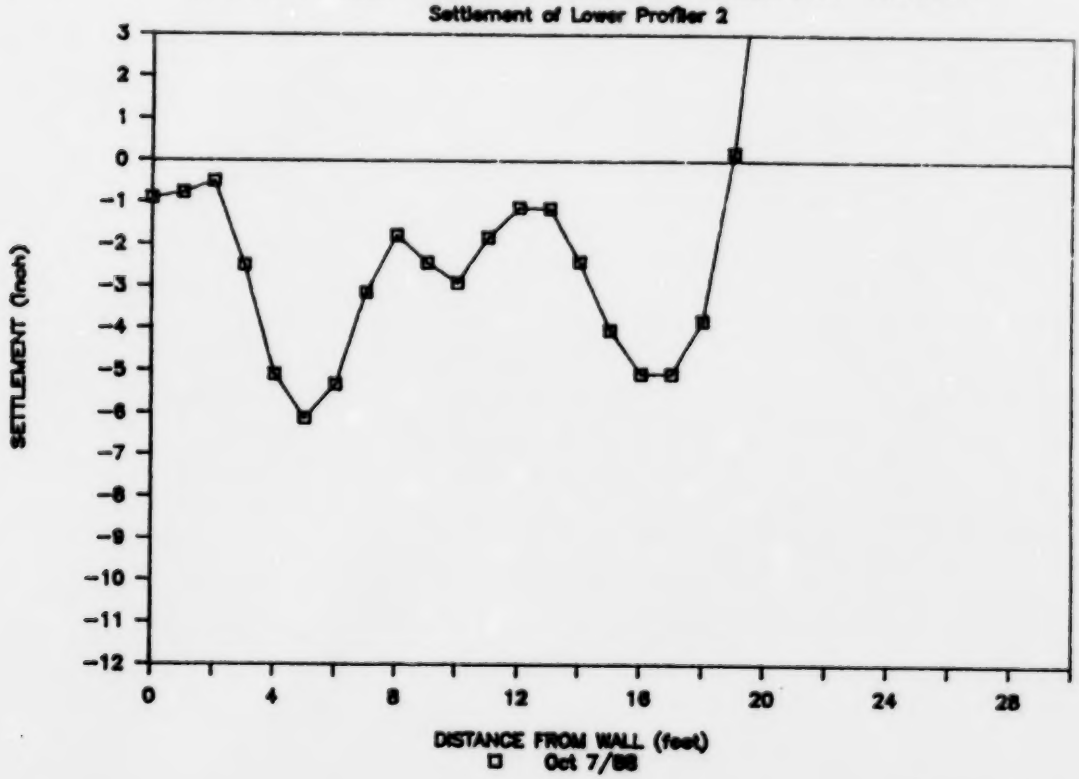


FIGURE 16: CARDINAL REINFORCED EARTH WALL



89-215
181757-RD

FIGURE 17: CARDINAL REINFORCED EARTH WALL

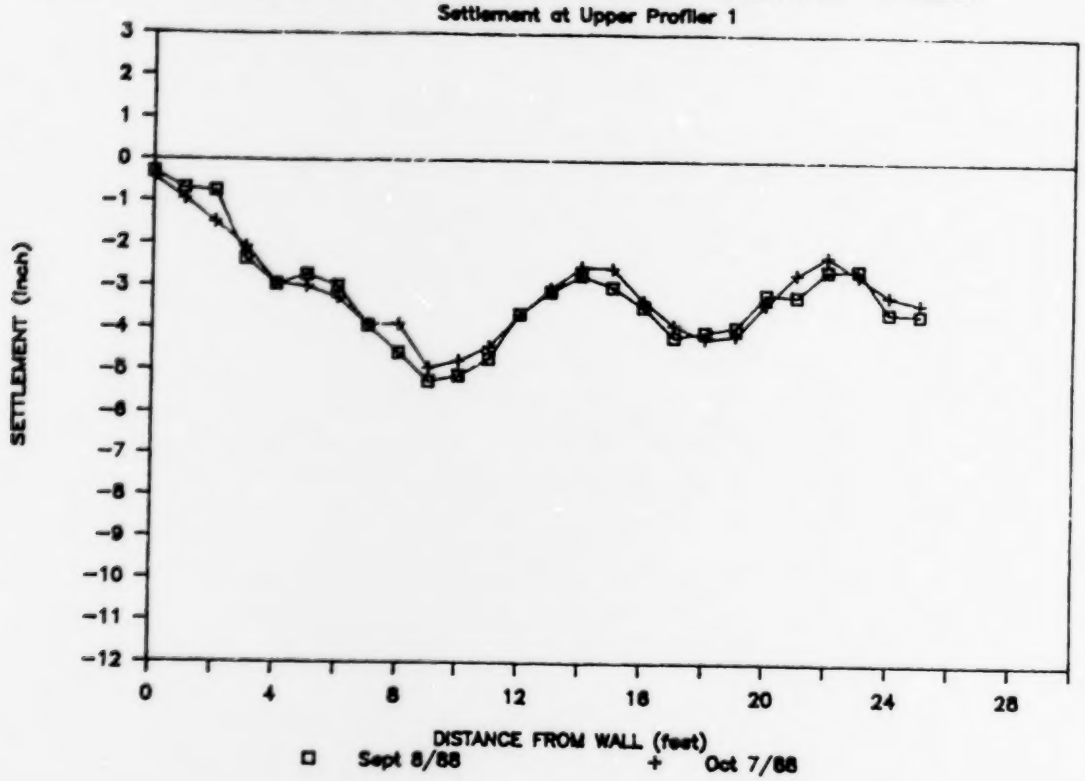


FIGURE 18: CARDINAL REINFORCED EARTH WALL

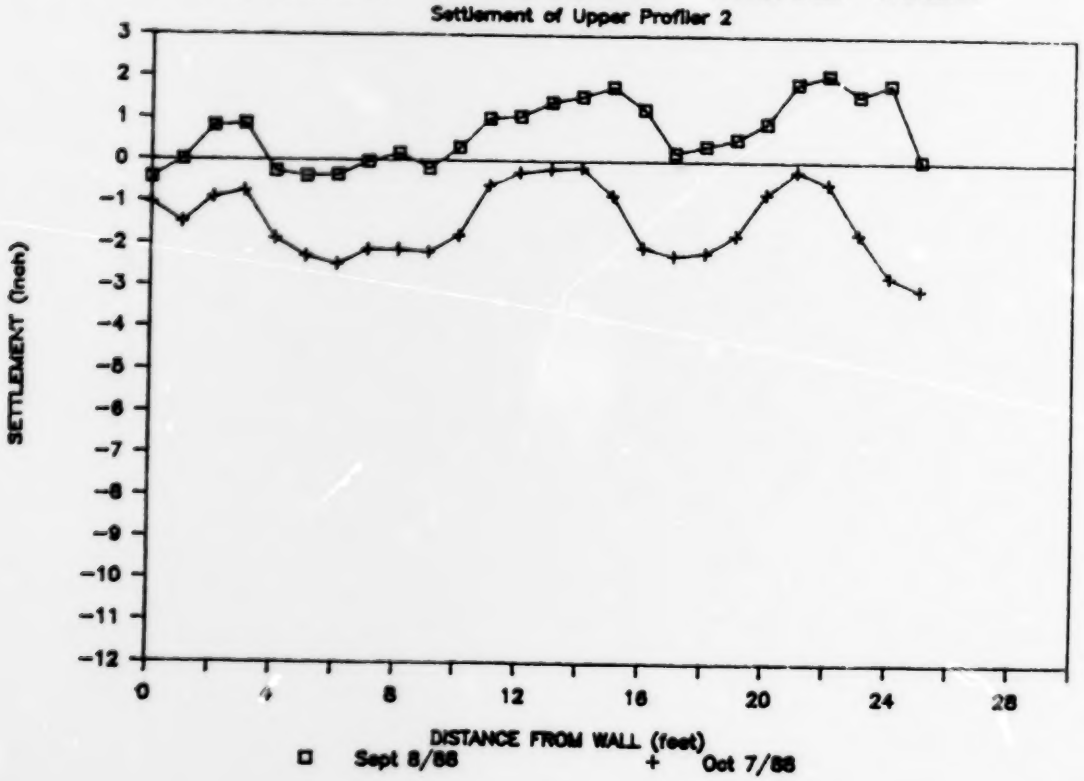


FIGURE 19: CARDINAL REINFORCED EARTH WALL

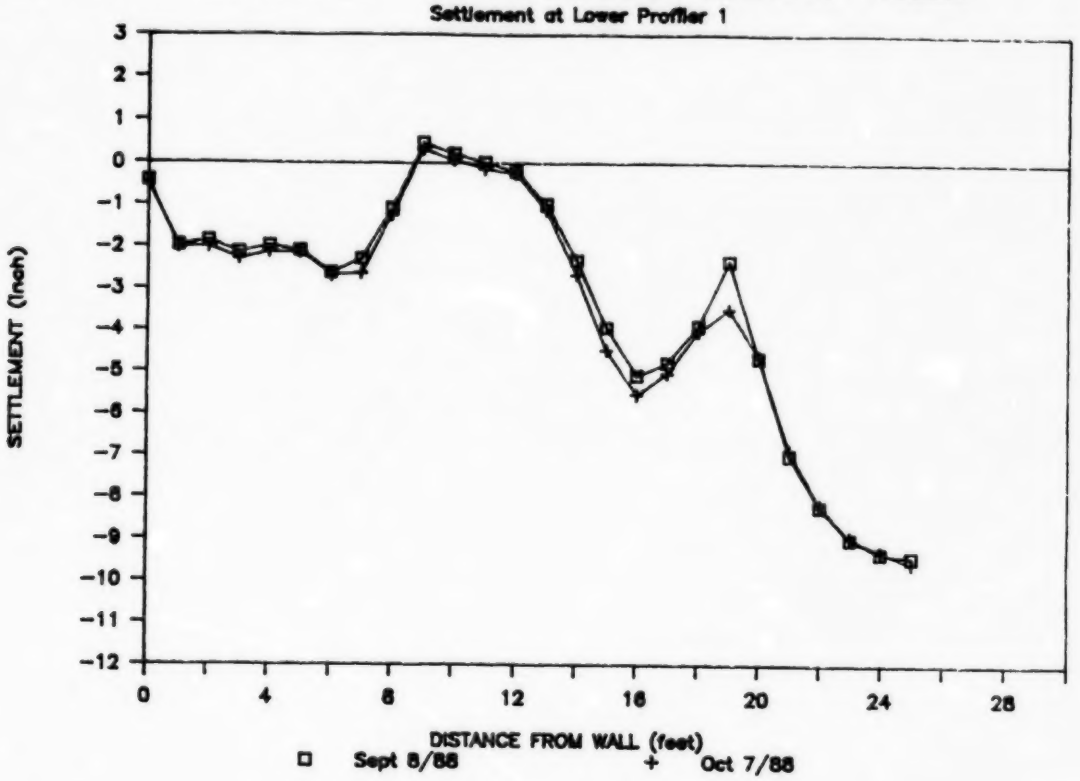
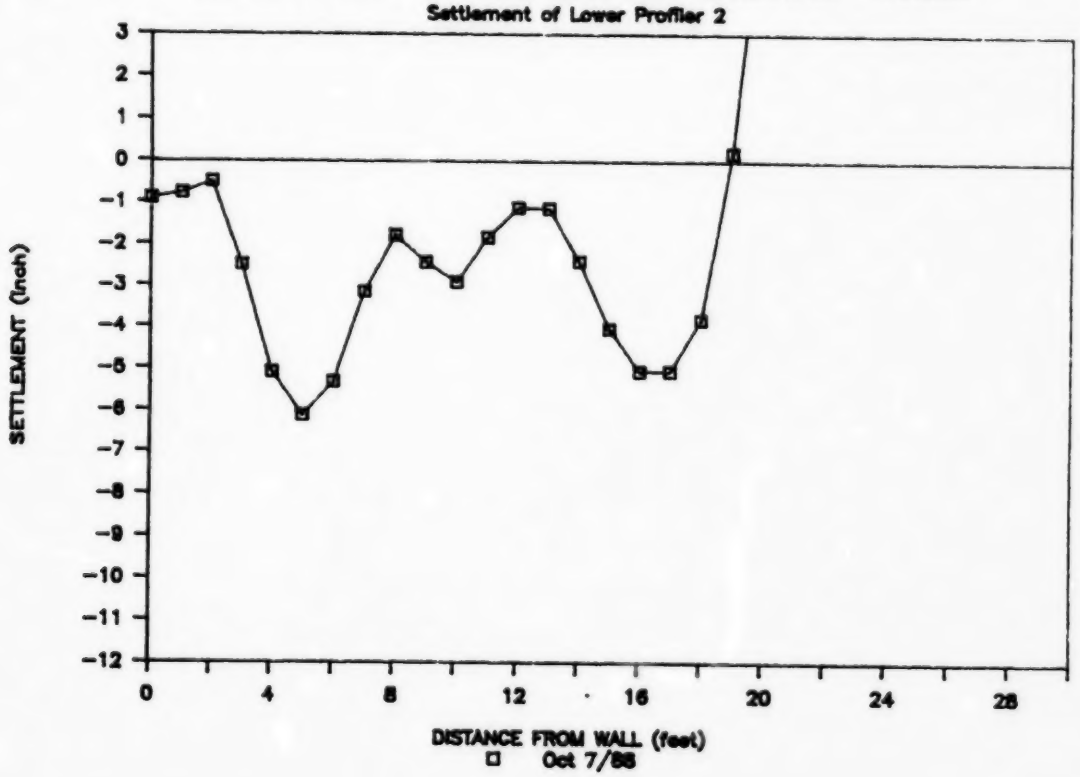


FIGURE 20: CARDINAL REINFORCED EARTH WALL



89-215
181755-RD